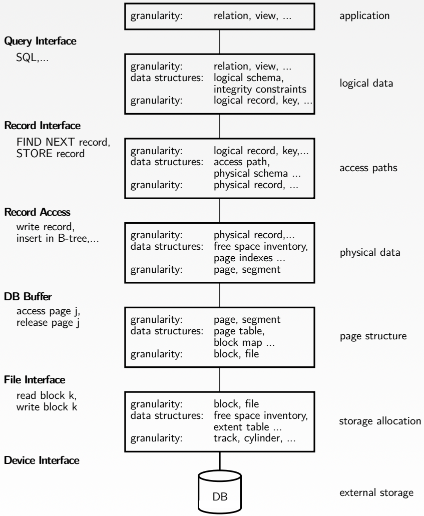
Lecture 12: Access Methods

CREATING THE NEXT®

Today's Agenda

Recap

A More Detailed Architecture



Anatomy of a Database System [Monologue]

- Process Manager
  - Connection Manager + Admission Control
- Query Processor
  - Query Parser
  - Query Optimizer (*a.k.a.*, Query Planner)
  - Query Executor
- Transactional Storage Manager
  - Lock Manager
  - Access Methods (*a.k.a.*, Indexes)
  - Buffer Pool Manager
  - Log Manager
- Shared Utilities
  - Memory, Disk, and Networking Manager

Access Methods

Access methods are alternative **ways for retrieving specific tuples** from a relation.

- Typically, there is more than one way to retrieve tuples.
- Depends on the availability of **indexes** and the conditions specified in the query for selecting the tuples
- Includes **sequential scan** method of **unordered table heap**
- Includes **index scan** of different types of **index structures**

We will look at these methods in more detail.

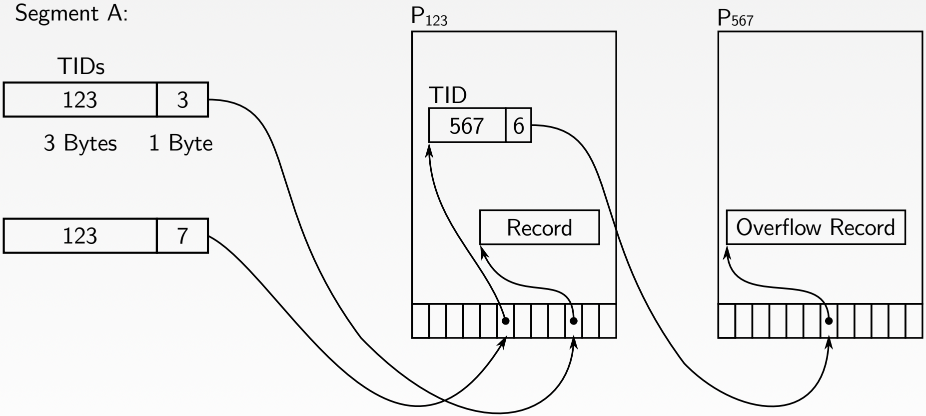
Internal Data Structures

The DBMS maintains several separate data structures

- for the data itself (storage and retrieval)
- for free space management
- for unusually large values
- for index structures to speed up access

Sequential Access: Table Heap

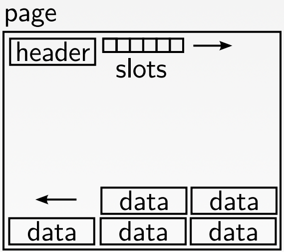
Slotted Pages



(TID size varies, but will most likely be at least 8 bytes on modern systems)

Slotted Pages (2)

Tuples are stored in slotted pages



- data grows from one side, slots from the other
- the page is full when both meet
- updates/deletes complicate issues, though
- might require garbage collection/compactification

Slotted Pages (3)

Header:

LSN	for recovery
slotCount	number of used slots
firstFreeSlot	to speed up locating free slots
dataStart	lower end of the data
freeSpace	space that would be available after compactification

Note: a slotted page can contain hundreds of entries!
Requires some care to get good performance.

Slotted Pages (4)

Slot:

offset	start of the data item
length	length of the data item

Special cases:

- free slot: offset = 0, length = 0
- zero-length data item: offset $>$ 0, length = 0

Slotted Pages (5)

Problem:

1. transaction T_1 updates data item i_1 on page P_1 to a very small size (or deletes i_1)
2. transaction T_2 inserts a new item i_2 on page P_1, filling P_1 up
3. transaction T_2 commits
4. transaction T_1 aborts (or T_3 updates i_1 again to a larger size)

TID concept $\Rightarrow$ create an indirection
but where to put it? Would have to move i_1 and i_2.

Slotted Pages (6)

Logic is much simpler if we can store the TID inside the slot

- borrow a bit from the TID (or have some other way to detect invalid TIDs)
- if the slot contains a valid TID, the entry is redirected
- otherwise, it is a regular slot

Depending on page size size, this wastes a bit space.
But greatly simplifies the slotted page implementation.

Slotted Pages (7)

One possible slot implementation:

T	S	O	O	O	L	L	L

1. if $T \neq 11111111_b$, the slot points to another record
2. otherwise the record is on the current page
   2.1 if $S = 0$, the item is at offset O, with length L
   2.2 otherwise, the item was moved from another page
      - it is also placed at offset O, with length L
      - but the first 8 bytes contain the original TID

The original TID is important for scanning.

Record Layout

The tuples have to be materialized somehow.

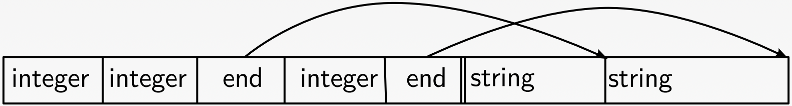
One possibility: serialize the attributes

integer	integer	length	string	integer	length	string

Problem: accessing an attribute is $O(n)$ in worst case.

Record Layout (2)

It is better to store offset instead of lengths



- splits tuple into two parts
- fixed size header and variable size tail
- header contains pointers into the tail
- allows for accessing any attribute in $O(1)$

Record Layout (3)

For performance reasons one should even reorder the attributes

- split strings into length and data
- re-order attributes by decreasing alignment
- place variable-length data at the end
- variable length has alignment 1

Gives better performance without wasting any space on padding.

NULL Values

What about NULL values?

- represent an unknown/unspecified value
- is a special value outside the regular domain

Multiple ways to store it

- either pick an invalid value (not always possible)
- or use a separate NULL bit

NULL bits allow for omitting NULL values from the tuple

- complicates the access logic
- but saves space
- useful if NULL values are common.

Compression

Some DBMS apply compression techniques to the tuples

- most of the time, compression is **not** added to save space!
- disk is cheap after all
- compression is used to **improve performance**!
- reducing the size reduces the bandwidth consumption

Some people really care about space consumption, of course.
But outside embedded DBMSs it is usually an afterthought.

Compression (2)

What to compress?

- the larger data compressed chunk, the better the compression
- but: DBMS has to handle updates
- usually rules out page-wise compression
- individual tuples can be compressed more easily

How to compress?

- general purpose compression like LZ77 too expensive
- compression is about performance, after all
- most system use special-purpose compression
- byte-wise to keep performance reasonable

Compression (3)

A useful technique for integer: variable length encoding

length (2 bits)	data (0-4 bytes)

	Variant A	Variant B
00	1 byte value	NULL, 0 bytes value
01	2 bytes value	1 byte value
10	3 bytes value	2 bytes value
11	4 bytes value	4 bytes value

Compression (4)

The length is fixed length, the compressed data is variable length

fixed	fixed	$len_1 len_2 len_3 len_4$	$comp_1$	$comp_2$	$comp_4$

Problem: locating compressed attributes

- depends on preceding compression
- would require decompressing all previous entries
- not too bad, but can be sped up
- use a lookup tuples per length byte

Compression (5)

Another popular technique: dictionary compression

Dictionary:

1	Berlin
2	München
3	Passauerstraße
...	...

Tuples:

city	street	number
1	3	5
2	3	7
...	...	...

- stores strings in a dictionary
- stores only the string id in the tuple
- factors out common strings
- can greatly reduce the data size
- can be combined with integer compression

Long Records

Data is organized in pages

- many reasons for this, including recovery, buffer management, etc.
- a tuple must fit on a single page
- limits the maximum size of a tuple

What about large tuples?

- sometimes the user wants to store something large
- e.g., embed a document
- SQL supports this via BLOB/CLOB

Requires some mechanism so handle these large records.

Long Records (2)

Simply spanning pages is not a good idea:

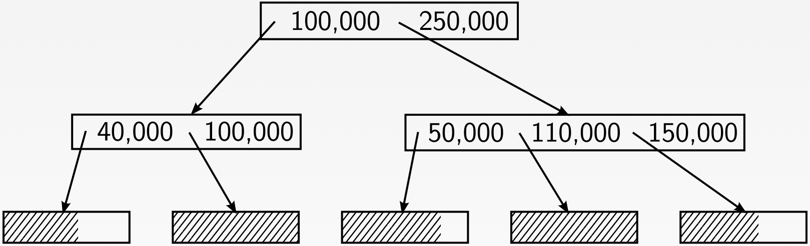
- must read an unbounded number of pages to access a tuple
- greatly complicates buffering
- a tuple might not even fit into main memory!
- updates that change the size are complicated
- intermediate results during query processing

Instead, keep the main tuple size down

- BLOBS/CLOBS are stored separate from the tuple
- tuple only contains a pointer
- increases the costs of accessing the BLOB, but simplifies tuple processing

Long Records (3)

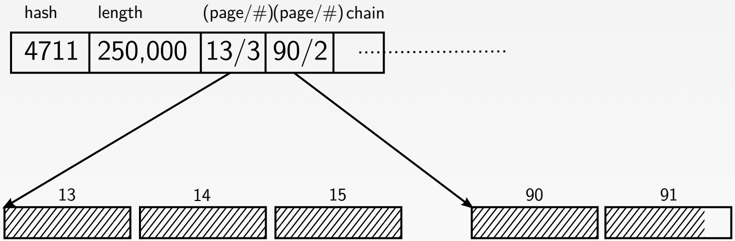
BLOBs can be stored in a B-Tree like fashion



- (relative) offset is search key
- allows for accessing and updating arbitrary parts
- very flexible and powerful
- but might be over-sophisticated
- SQL does not offer this interface anyway

Long Records (4)

Using an extent list is simpler



- real tuple points to BLOB tuple
- BLOB tuple contains a header and an extent list
- in worst case the extent list is chained, but should rarely happen
- extent list only allows for manipulating the BLOB in one piece
- but this is usually good enough
- hash and length to speed up comparisons

Long Records (5)

It makes sense to optimize for short BLOBs/CLOBs

- users misuse BLOBs/CLOBs
- they use CLOB to avoid specifying a maximum length
- but most CLOBs are short in reality
- on the other hand some BLOBs are really huge
- the DBMS cannot know
- so BLOBs can be arbitrary large, but short BLOBs should be more efficient

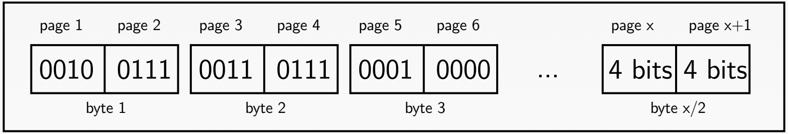
Approach:

1. BLOBs smaller than TID are encoded in BLOB TID
2. BLOBs smaller than page size are stored in BLOB record
3. only larger BLOBs use the full mechanism

Free Space Inventory

Problem: Where do we have space for incoming data?

Traditional solution: free space bitmap



Each nibble indicates the fill status of a given page.

Free Space Inventory (2)

Encode the fill status in 4 bits (some system use only 1 or 2):

- must approximate the status
- one possibility: data size / $\frac{\text{page size}}{2^{bits}}$
- loss of accuracy in the lower range
- logarithmic scale is often better
- $\lceil \log_2(\text{text size}) \rceil$
- or a combination (logarithmic for lower range, linear for upper range)

Encodes the free space (alternative: the used space) in a few bits.

Free Space Inventory (3)

When inserting data,

- compute the required FSI entry (e.g., $\leqslant 7$)
- scan the FSI for a matching entry
- insert the data on this page

Problem:

- linear effort
- FSI is small, for 16KB pages 1 FSI page covers 512MB
- but scan still not free
- only 16 FSI values, cache the next matching page (range)
- most pages will be static (and full anyway)
- segments will mostly grow at the end
- cache avoids scanning most of the FSI entries

Allocation

Allocating pages (or parts of a page) benefits from application knowledge

- often larger pieces are inserted soon after each other
- e.g. a set of tuples
- or one very large data item
- should be allocated close to each other

Allocation interface is usually

$$allocate(min, max)$$

- *max* is a hint to improve data layout
- some interfaces (e.g., segment growth) even implement over-allocation
- reduces fragmentation

Index Structures

Data is often indexed

- speeds up lookup
- de-facto mandatory for primary keys
- useful for selective queries

Two important access classes:

- point queries
  find all tuples with a given value (might be a compound)
- range queries
  find all tuples within a given value range

Support for more complex predicates is rare.

Random Access: B-Tree Index

B-Tree

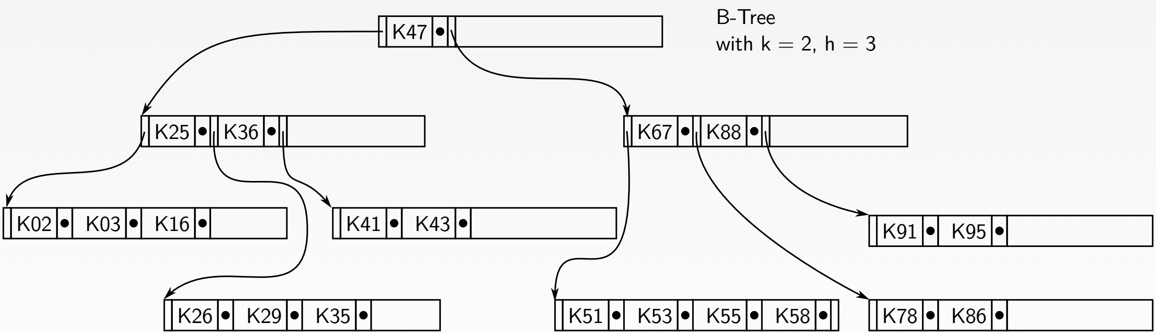
B-Trees (including variants) are the dominant data structure for external storage.

Classical definition:

- a B-Tree has a degree k
- each node except the root has at least k entries
- each node has at most $2k$ entries
- all leaf nodes are at the same depth

B-Tree (2)

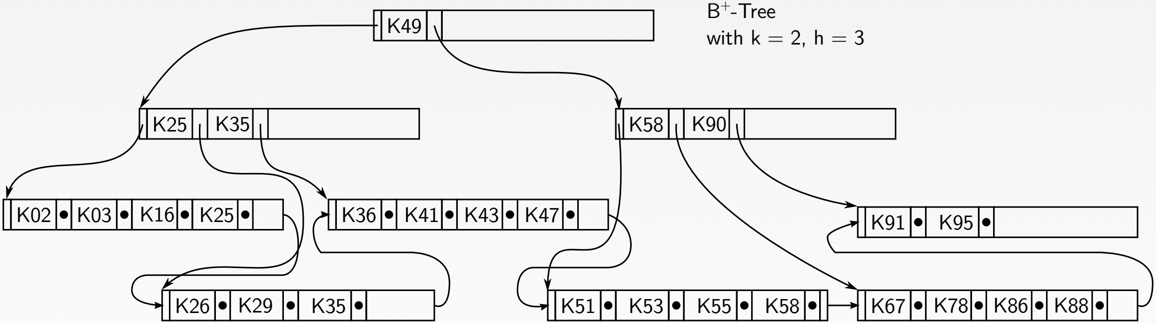
Example:



The • is the TID of the corresponding tuple.

B^+-Tree

Most DBMS use the B^+-Tree variant:



B^+-Tree
with k = 2, h = 3

- key+TID only in leaf nodes
- inner nodes contain separators, might or might not occur in the data
- increases the fanout of inner nodes
- simplifies the B-Tree logic

Page Structure

Inner Node:

LSN	for recovery
upper	page of right-most child
count	number of entries
key/child	key/child-page pairs
...	...

Leaf Node:

LSN	for recovery
~0	leaf node marker
next	next leaf node
count	number of entries
key/tid	key/TID pairs
...	...

Similar to slotted pages for variable keys.

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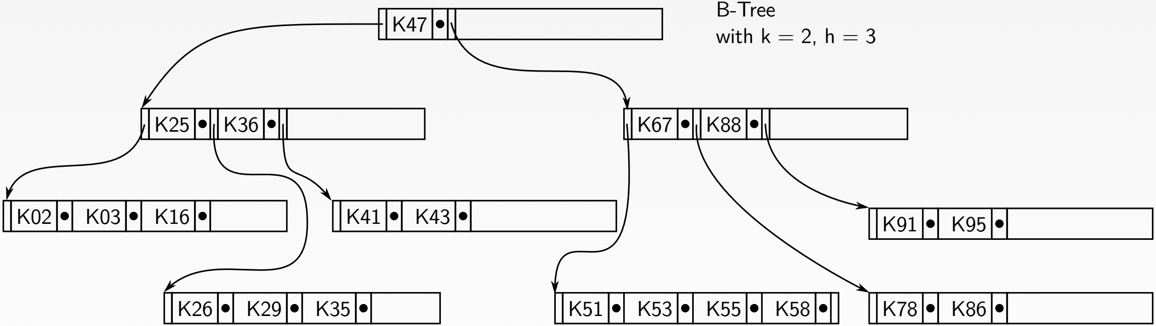

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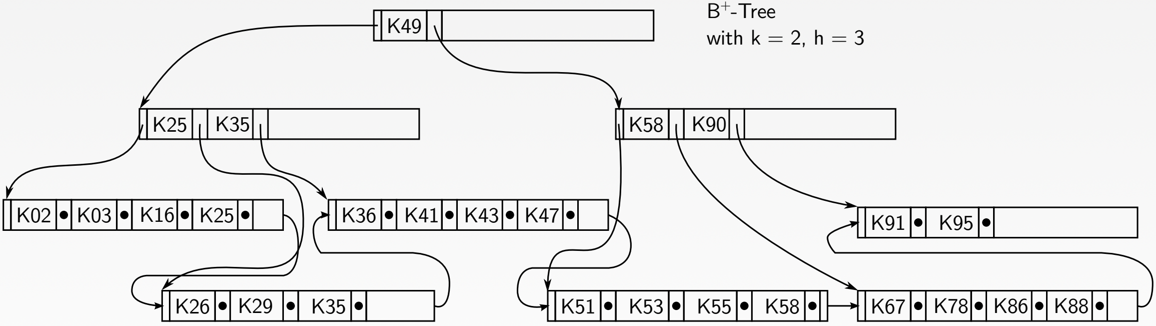

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Random Access: Hash Index

Hash Tables

- Hash tables are fast data structures that support O(1) look-ups
- Used all throughout the DBMS internals.
  - Examples: Page Table (Buffer Manager), Lock Table (Lock Manager)
- Trade-off between speed and flexibility.

Limitations of Hash Tables

- Hash tables are usually **not** what you want to use for a indexing tables
  - Lack of ordering in widely-used hashing schemes
  - Lack of locality of reference $\longrightarrow$ more disk seeks
  - Persistent data structures are much more complex (logging and recovery)
  - Reference

Hash-Based Indexes

In main memory a hash table is usually faster than a search tree

- compute a hash-value h, compute a slot (e.g., $s = h \bmod |T|$, access the table $T[s]$
- promises $O(1)$ access
- (if everything works out fine)

A DBMS could profit from this, too. But:

- random I/O is very expensive on disk
- collisions are problematic (e.g., when chaining)
- rehashing is prohibitive

But there are hashing schemes for external storage.

Hash-Based Indexes (2)

Hash indexes are not as versatile as tree indexes:

- only support point query
- range queries are very problematic
- order preserving hashing exists, but is questionable
- quality of the hash function is critical

As a consequence, mainly useful for primary key indexes

- unique keys
- key collisions would be very dangerous
- how to delete a tuple with an indexes attribute of there are 1 million other tuples with the same value?
- can be fixed by separate indexing within duplicate values (complicated)

Conclusion

- Access methods are the alternative ways for retrieving specific tuples
- We covered two access methods: sequential scan and index scan
- Sequential scan is done over an unordered table heap
- Index scan is done over an ordered B-Tree or an unordered hash table
- In the next lecture, we will learn about hash indexes